# LETTERS TO THE EDITOR

## PHYSICAL SCIENCES

### The Galactic Halo

THE halo of our galaxy is a nearly spherical region containing very old stars which have a smaller content of heavy elements than our Sun. There is no detailed model for its formation. It is usually assumed that somehow a cloud of gas condensed to form our galaxy, and that the halo stars were formed during the collapse process and left with a nearly spherical distribution[1]. In that case, and in view of the success of the theories of nucleosynthesis in stars, it is very puzzling that the halo stars should have any heavy elements at all.

We reconsidered this problem in connexion with our preparations for the symposium on the chemical evolution of the galaxy recently held at the California Institute of Technology in honour of the sixtieth birthday of J. L. Greenstein. This exercise was a new version of a study carried out a few years ago[2] in which the chemical history of the galaxy is followed by numerically integrating the effects of stellar evolution. The general approach was similar to that of the previous study, except that more details of the integrations could be recorded using the storage of the 360/95 computer of the Goddard Institute for Space Studies. The principal difference between the two studies arose in the assumptions which we have now made about the details of stellar evolution. We shall prepare a full report for publication elsewhere; in this report we give only the principal arguments and conclusions which we reached having a bearing on the origin and evolution of the galactic halo.

Our assumptions about stellar evolution have been influenced very heavily by recent studies of supernova explosions by Arnett[3]. For massive stars up to twenty solar masses, we assumed that a complete nuclear explosion would occur, leaving no remnant but injecting into the interstellar medium the main products of nucleosynthesis between carbon and the iron equilibrium peak[4,5]. For more massive stars, we assumed that the implosion would form a Schwarzschild singularity, that is, a black hole or "collapsar". In both cases we assumed that thirty per cent of the initial main sequence mass would be lost in stellar winds during stellar evolution.

The rate of star formation was governed by the assumption that the gas content of the galaxy declined exponentially, reaching five per cent at $1\cdot5\times10^{10}$ yr (a number chosen to fit cosmochronological considerations). We assumed the same stellar birth-rate function as in the earlier study, where it was taken from the work of Salpeter[6] and Limber[7].

As before, we found that the heavy element content of the galaxy rose very quickly in the first $2\times10^{9}$ yr, and that it increased only slowly after that. The present calculations, however, indicated that about ten per cent of all stars of slightly less than the solar mass (which would never have evolved beyond the main sequence) would contain 15 per cent or less of the solar content of heavy elements. Observations show that such stars are extremely rare, however, and that most stars have a heavy element content within a factor three of the solar content. We therefore felt forced to the conclusion which was earlier reached by Schmidt[8]: in the early history of the galaxy almost all the stars formed were more massive than the Sun.

This is consistent with current thinking about star formation. Fragmentation is greatly assisted during the collapse of an interstellar cloud if strong density-dependent cooling is present. Such cooling reduces the velocity of propagation of pressure waves and hence isolates one part of the gas from its neighbouring part. Cooling is very inefficient below about $10^4$ K if heavy elements are not present in the gas to form grains and ions with low-lying excited states. It is therefore reasonable to expect that only quite massive stars can have been formed in the galaxy until the heavy element content of the gas rose to a significant fraction of the solar value. For the purposes of our numerical exploration we assumed that only that part of the stellar birth-rate function above ten solar masses was formed by star formation until the content of elements heavier than helium in the interstellar gas reached 0·005 of the mass, about one-third of the solar value.

The galactic evolutionary histories which we computed had a number of strange aspects, but one feature stood out. In the original birth-rate function, about five per cent of the mass ends up in collapsars according to our stellar evolution assumptions. In the revised birth-rate assumptions the collapsar mass fraction becomes about an order of magnitude larger. This feature points the way to the following suggestions about the early history of our galaxy.

Suppose, as is usually done, that a cloud of gas collapses to form our galaxy. Suppose also that about half of the mass of this gas promptly forms massive stars (something like our revised early birth-rate function). These stars contain no heavier elements and hence are likely to have high surface temperatures, of order $10^5$ K. The residual gas is likely to be maintained at a similar gas kinetic temperature and to form a roughly spherical body having an approximation to hydrostatic equilibrium and a radius of order $10^5$ pc. The rapid evolution of the massive stars will mix substantial amounts of heavy elements into this halo gas. This heavy element contamination greatly increases the cooling efficiency of the halo gas, thus allowing the formation of low mass stars in the halo and simultaneously allowing the halo gas to collapse to form the galactic disk, because the thermal pressure is suddenly reduced.

We have run some models of the galaxy based on this picture. We doubled the mass of the galaxy and put all the additional mass into stars in the first evolutionary time step. This has given us the best fit to the various observed abundance criteria which we wished to fit by our computed galactic histories. While this success is gratifying, we emphasize that a large number of assumptions is involved, so that the only conclusion which can properly be drawn is that our current assumptions about stellar evolution are consistent with our picture of the formation and evolution of the galactic halo.

These calculations indicate that about half the present mass of the galaxy is in the form of collapsars. The many assumptions mean that this number can only be taken as a rough indication of what we should expect. It is not in conflict with observations, however. We must expect the galaxy to be nearly twice as massive as usually assumed, with most of the extra mass consisting of collapsars distributed throughout the halo. This distribution will have very little effect on the dynamical motions of the stars in the galactic disk. Analyses of the motions of the stars in the solar neighbourhood perpendicular to the galactic disk indicate that some thirty per cent of the local mass density is in an unseen form, subject to the assumption that the unseen mass is strongly concentrated to the disk[9]. If the unseen mass has a more nearly spherical distribution, however, its mass can be very much greater than this[10].

For many years it has been a puzzle that giant elliptical galaxies have such a high mass-to-light ratio[11]. The present considerations lead us to suggest that the majority of the mass of such galaxies is in the form of collapsars.

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## An Oscillating State as an Alternative to Gravitational Collapse

THE possibility of an oscillating universe is often disputed on the grounds that oscillations are not possible when there is no equilibrium position[1]. By the same argument, gravitational collapse can be considered as the only alternative when the mass is over critical (there is no configuration of equilibrium for such a big mass). The argument, however, cannot be generalized from the cosmological case to the case of a big mass, as we will see.

The existence of a critical mass of the order of that of the Sun follows from the equation of state obeyed by matter. This can be seen from the following example of a solution representing a mass as big as desired in equilibrium.

$$ds^2 = \frac{-2}{1-ar^2}\,dr^2 - r^2\,(d\theta^2 + \sin^2\theta\,d\varphi^2) + ar^2\,dt^2 \qquad (1)$$

from which we obtain

$$8\pi\rho = (1/2r^2) + (3a/2) \qquad (2)$$

$$8\pi p = (1/2r^2) - (3a/2) \qquad (3)$$

The equation of state is

$$\rho = p + k \text{ (with } k = 3a/8\pi) \qquad (4)$$

The element can be joined smoothly to the Schwarzschild exterior solution

$$ds^2 = -\left(1-\frac{2m}{r}\right)^{-1} dr^2 - r^2\,d\,\Omega^2 + \left(1-\frac{2m}{r}\right)dt^2 \qquad (5)$$

giving for the gravitational mass the value

$$m = (1/3)\ (8\pi k)^{-1/2} \qquad (6)$$

and for the radius

$$R = (8\pi k)^{-1/2} \qquad (7)$$

Pressure and density become infinite at the origin, but there is a theorem[2] applicable in this case which ensures the existence of solutions with the same equation of state, and with a total mass as near as desired to that of our solution provided that the central pressure and density are high enough, though finite.

It is possible therefore to have as large a mass as desired in equilibrium provided we admit an equation of state of the form $\rho = p + k$ small enough. Oppenheimer and Volkoff's proof[3] of the existence of a critical mass of the order of that of the Sun relies on the known equation of state for cold neutron matter.

Misner and Zapolsky[4] have generalized the proof of ref. 3 for the case when matter with over nuclear density obeys an equation of state of the form $p = \rho(\gamma - 1)$ with $1 \leq \gamma \leq 2$ while for under nuclear densities the equation of state is the known equation for cold neutron matter.

Comparing my solution with that of Misner and Zapolsky, both propose the same equation of state for the core (if we take $\gamma = 2$). The essential difference is that the equation $\rho = p$ is considered by Misner and Zapolsky to be valid for over nuclear densities only, while in our case (for $k$ very small) the equation $\rho = p$ remains approximately valid for a considerable range of under nuclear densities. When the equation $\rho = p$ can be extended to a quantity of matter sufficiently larger than that considered by Misner and Zapolsky, there may be equilibrium configurations for masses as great as desired.

The approach of Misner and Zapolsky is sound, so I do not propose my solution as a model for big masses in equilibrium. I accept therefore that there is no configuration of equilibrium for big masses of cold neutron matter. As such big masses collapse, however, most of the matter may become of over nuclear density.

The existence of restoring forces must now be studied with due regard to the equation of state prevailing in the dynamical process during which there exists a much higher ratio of matter with over nuclear density to matter with under nuclear densities than in the static case.

Misner and Zapolsky did not calculate the possibility of equilibrium for such higher ratios of matter obeying the $\rho = p$ equation to matter not obeying it (such higher ratios are unrealistic in the static case). My example proves that in this case there is an equilibrium configuration and therefore there may be restoring forces to this position of equilibrium.

An over critical mass could therefore oscillate in the following way: (1) It starts collapsing because it cannot remain in equilibrium. (2) As it collapses, the ratio of mass with over nuclear to mass with under nuclear density increases and the equation of state of that part of the body, the density of which goes from under nuclear density to over nuclear density, does change. As a result, restoring forces build up. (3) Under the effect of the restoring forces the collapse stops, to be followed by the expansion of the body. (4) While expanding, the ratio of over nuclear densities to under nuclear densities decreases. The body therefore does not cross a position of equilibrium but completes the cycle by reaching the initial state for which no equilibrium position exists.

It would be interesting to establish the precise ratio (as a function of total mass) which separates the cases for which there is or there is not restoring forces. It would be helpful to calculate the limiting mass for which the restoring forces are reversing the collapsing movement before the crossing of the Schwarzschild radius. When the Schwarzschild radius is to be crossed (from the point of view of a comoving observer), the body is to be considered as a collapsing non-oscillating one from the point of view of